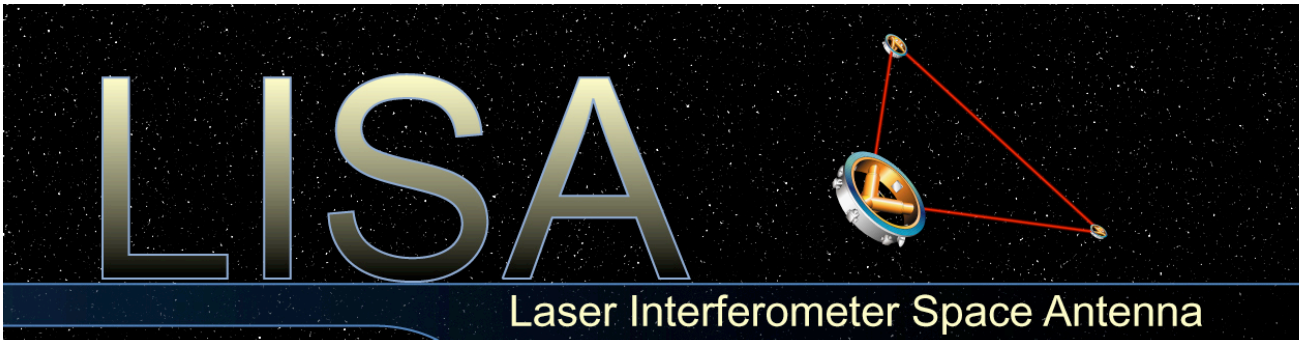


LISA Newsletter
August 2004
Volume 1
Number 2

New eyes on the sky:
Gravitational waves and a new era of multi-messenger astronomy

Karen Willacy (JPL) & Shane Larson (Penn State)

The Laser Interferometer Space Antenna (LISA) is the first dedicated space-based gravitational wave observatory. It is a joint NASA/ESA mission and will measure the distortions in spacetime caused by the most violent events in the Universe e.g. the mergers of supermassive black holes in the centers of galaxies. It will explore the fundamental nature of gravity and open a new window on the Universe. The planned launch date for LISA is 2013.

Contributions to the LISA newsletter on both technology and science relevant to the mission are welcome.
Please contact Karen.Willacy@jpl.nasa.gov

Nearly all our knowledge of the distant reaches of the Cosmos is based on observations of electromagnetic (EM) radiation across the spectrum, from radio waves to gamma rays. EM astronomy has painted a rich and varied picture of the Universe, shaping our current understanding of the formation, growth and evolution of galaxies, stars and spacetime itself. So why should an astronomer who is accustomed to observing the Universe in the electromagnetic spectrum care about gravitational waves? Here we consider some of the differences between the two types of radiation and how this new multi-messenger perspective will expand our understanding of dynamic astrophysical phenomena (Figure 1).

EM radiation is plentiful and readily interacts with ordinary matter, whether that matter be gas and stellar material, silicon detectors in

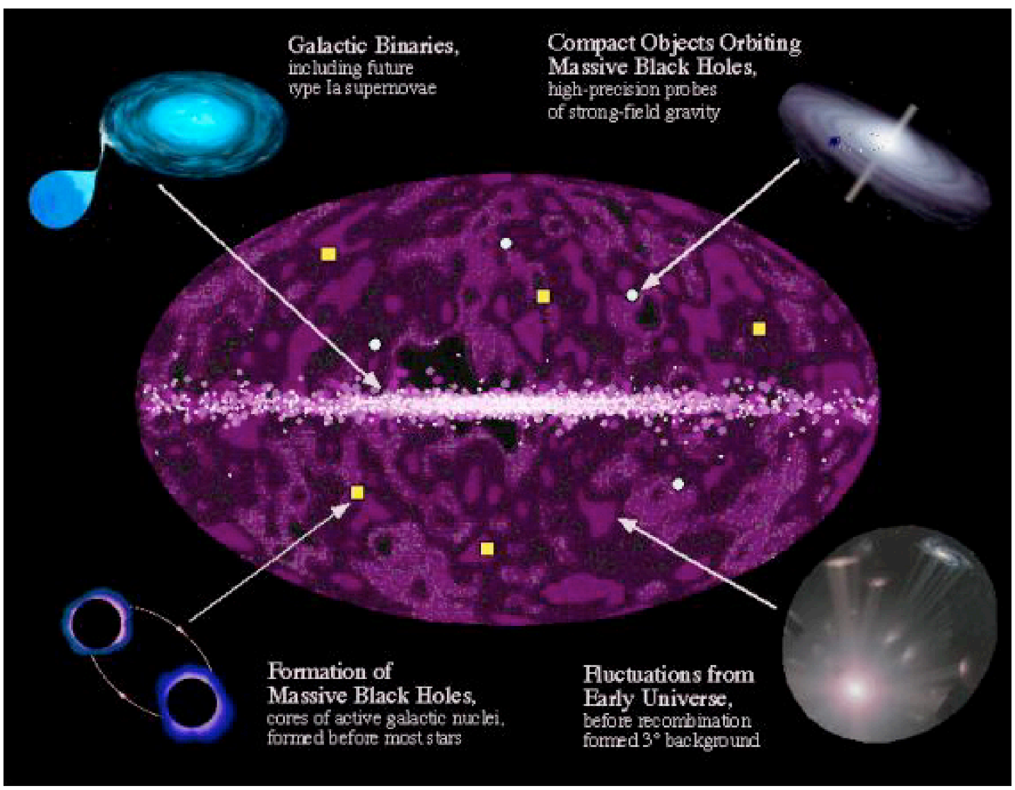


Figure 1: Many astrophysical phenomena should radiate in both gravitational waves and electromagnetic radiation.

telescopes or the soft retinal tissue of the human eye. The fact that photons interact so easily with matter is both good and bad. On the one hand, photons are easily generated in astrophysical systems by magnetic field interactions, thermodynamic processes and plasma dynamics. The wavelengths, polarization and luminosity of the light that is emitted contain detailed information about the energetics and dynamics of the system. Observers who detect these streams of photons attempt to decode the message carried in the light, and deduce the character of the system that produced the radiation. On the other hand, photons propagating though the Universe will readily interact with anything they encounter, causing information to be lost as they travel between the parent system and the observer. Intervening plasmas and magnetic fields will change the polarization state of the light, dust will attenuate it and gas will absorb the photons and reradiate at other wavelengths. Photons can even be stopped at their source, unable to find a clear path out of dense and highly energetic systems (e.g. the core of a supernova explosion).

In traditional astrophysics, the problems associated with the loss of information are often mitigated with 'multi-messenger astronomy', i.e. looking at a system in many different wavelengths (optical, x-ray etc) and if possible with astroparticles (cosmic rays and neutrinos). Here at the start of the 21st century, a new messenger is being added to the list of tools available to observers: gravitational waves.

Like their EM brethren, gravitational waves contain information about the astrophysical dynamics of the parent system in their wavelength, intensity and polarization state. Gravitational waves are generated by the dynamical motion of mass and propagate away from the system as coherent oscillations of spacetime itself (by comparison EM waves are generated by the dynamical motion of charged particles and propagate as oscillations of the electromagnetic field). Like EM waves, gravitational waves have two polarization states, which contain information about the geometric structure of the dynamics that generated the waves. Gravitational waves are quadrupolar because there is only a single kind of mass, as compared to EM waves, which have a dipolar character because of there are two kinds of charges (positive and negative). The two gravitational wave polarization states are called '+' (plus) and 'x' (cross) and the quadrupolar nature of the waves can be seen by observing how the waves interact with a simple detector, like a ring of test particles (Figure 2); they squeeze the detector along one axis, while simultaneously stretching it along an orthogonal axis. The two polarization states are identified by the orientation of the axes along which the stretching and squeezing occurs. This interaction is central to the design concept of modern gravitational wave observatories like LISA, which are stretched and squeezed in a similar way.

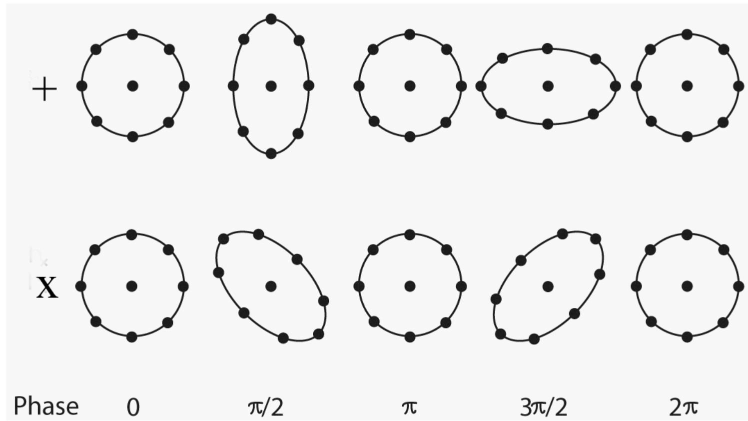


Figure 2: The effects of a passing gravitational wave on a ring of test particles, showing how the ring is compressed in one direction and simultaneously stretched in the other. This gives rise to the two gravitational wave polarizations.

Unlike photons, gravitational waves do not readily interact with matter. As an astronomical messenger this is ideal because the waves are not prone to the same problems as photons. Gravitational waves will propagate promptly out of dense, compact systems (like collapsing stars) and will freely traverse the Universe without impediment or attenuation by intervening matter (note that gravitational waves will experience cosmological effects, such as redshift and lensing). However, this weak coupling to matter means they pass through our detectors without any large effect on them, leaving only the faintest whisper of their passage. This makes the technological challenges of building observatories more difficult, but if we hear these waves, the payoff in scientific returns will be enormous.

How will photon astronomy and gravitational wave astronomy be able to work together to bring us a deeper understanding of high-energy astrophysical systems? This is a branch of astronomy that has yet to be explored to its full potential, but lets consider several examples of how these two observing paradigms might work in concert with each other.

One of the most exciting prospects in gravitational wave astronomy is that observatories like LISA might be sensitive to gravitational waves generated at the earliest moments after the Big Bang. Because gravitational waves interact poorly with matter, these primordial gravitational waves propagate easily through the hot dense early Universe. By contrast, the early Universe was very unfriendly to photon propagation, preventing the free streaming of EM waves until around 300,000 years after the Big Bang; these photons reach us today as the Cosmic Microwave Background (CMB). Together with the CMB, detection of a Cosmic Gravitational-wave Background (CGB) will allow us to probe the earliest era of structure organization and give us clues to the origin and growth of the density perturbations that currently are visible in the CMB data (Figure 3).

The high redshift Universe (z > 1) is also an important target for gravitational wave astronomy, where LISA will probe the merging of supermassive black holes. Detecting coincident EM and gravitational wave signals from a merging source will allow us to readily break degeneracies and address systematic uncertainties in current cosmological measurements which seek to determine the composition of the Universe in terms of normal and dark matter.

LISA will be sensitive to the cacophony of gravitational waves produced by interacting white dwarf binaries in the galaxy (Figure 4). In general these systems are dim in the EM spectrum and not resolvable with current telescope technology. By contrast, LISA will be sensitive to some 10 million systems across the entire galaxy with several thousand being loud enough for LISA to individually resolve and study. With the addition of gravitational waves information, seeing small changes in the orbital frequency might yield information about mass transfer in these systems, their spatial distribution and their numbers which in turn will tell us something about the history of stellar evolution in the Milky Way. Directly comparing EM and gravitational wave observations will provide an opportunity to study the fundamental character of general relativity and also could yield a method for directly measuring the physical size of the accretion disk.

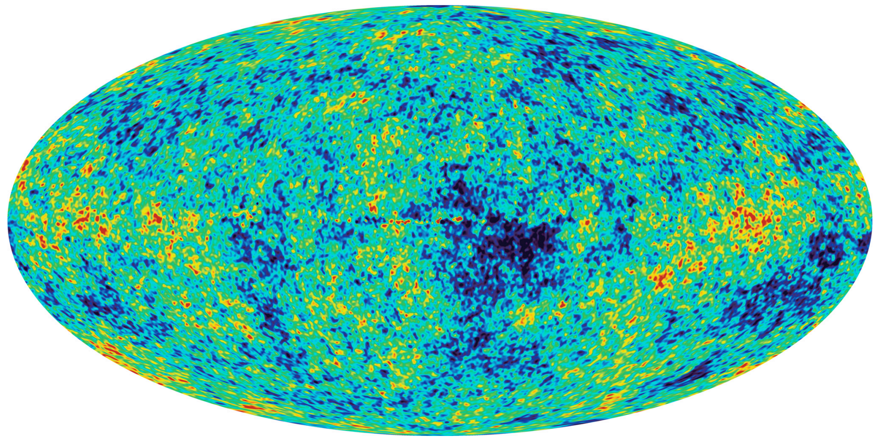


Figure 3: The Cosmic Microwave Background (CMB) reaches us from 300,000 years after the Big Bang, while gravitational waves will come from much earlier. Together, the CMB and the cosmic gravitational wave background could disentangle the history of the very early Universe.
Image credit: WMAP Science Team/ NASA

The direct detection of gravitational waves will be an exciting achievement in its own right, but the legacy of observatories such as LISA will be in the use of gravitational waves to study high energy astrophysics. The detection of gravitational waves will 'open a new window on the Universe', allowing us to probe aspects of the Universe that are inaccessible to EM astronomy and provide information complementary to that obtained by traditional methods. The results expected from LISA will be of interest not just to those working in the field of gravitational waves and relativity but also to the whole astronomical community.

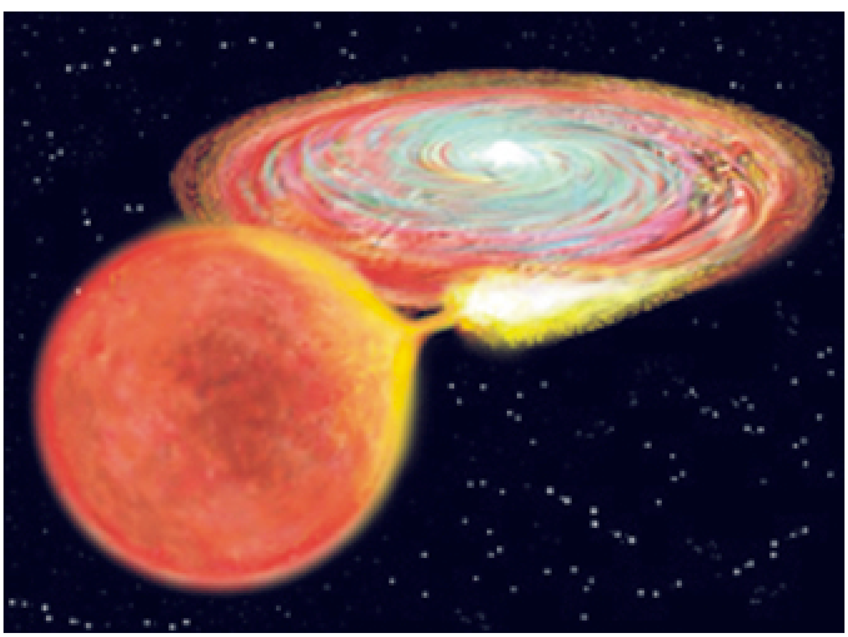


Figure 4: Bright, mass-transferring binaries will be visible to both LISA and conventional electromagnetic telescopes, allowing simultaneous observations.

Further reading:

N. J. Cornish, (2002) Phys. Rev. D **65** 022004

J. R. Gair et al. (2004) gr-gc/04051337 (to appear in GWDAW8 proceedings)

D. E. Holz & S. A. Hughes (2003) Classical & Quantum Gravity **20** S63

S. A. Hughes (2002) MNRAS **331** 805

S. L. Larson & W. A. Hiscock (2001) Phys. Rev. D. **61** 104008G.

Nelemans et al. (2001) A&A **375** 890

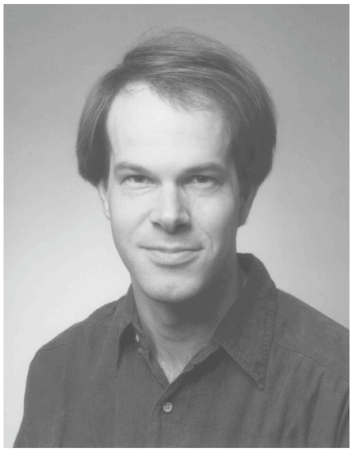
K. S. Thorne (1987) in *300 Years of Gravitation* (S Hawking & W. Israel, eds) CUP p380

Upcoming events

HEAD Divisional Meeting, 8th – 11th September (2004), New Orleans

LISA Science and Engineering Workshop, 20th – 23rd September 2004, ESTEC

Meet a scientist – Sterl Phinney



Sterl's webpage can be found at www.its.caltech.edu/~esp

Sterl Phinney is a Professor of Theoretical Astrophysics at the California Institute of Technology. His research interests include high energy relativistic astrophysics and low energy Newtonian astrophysics. He is also the chair of the Sources and Data Analysis Working Group of the LISA International Science Team which is in charge of studying the sources that LISA will observe and simulating the data streams we can expect from them. He tells us about how he first got interested in science and his interest in the LISA mission.

I first got interested in astronomy when my grandfather gave me a Larousse Encyclopedia of Astronomy. It was by Gérard de Vaucouleurs and had beautiful pictures in it. It impressed me a lot and I think I was about 5 when I decided I wanted to be an astronomer. I changed my mind a few times after that but I came back to it. In college I discovered I really liked physics and since I was interested in astronomy I wanted to apply physics to astronomy. So I became a theoretical astrophysicist because that is what theoretical astrophysicists do – they figure out how the world works and use the results of experimental physics on earth to try to predict what happens everywhere else in the Universe.

I've been involved with LISA since 1996 and chaired NASA's LISA mission definition team from 1997-2001. LISA will do many things that I am interested in. As a person with a not very long attention span I try to change what I do every five years or so and LISA does lots of things, all of which I have been interested in at some point in my career. So for me it was the perfect mission. I've been interested in binary stars and close pairs of stars and how they interact and exchange mass with each other and LISA will detect tens' of thousands of the most interesting of these systems. My Ph.D. thesis long ago was in part on the extraction of energy from rotating supermassive black holes and LISA will provide exquisite measurements of that. Relativity is one of the most mind-boggling but poorly-tested parts of physics, and LISA will provide many new tests of its correctness.

One of the ways it can do this is to detect gravitational waves produced by bodies such as black holes or stars, orbiting a black hole. The orbits of the bodies will give us detailed measurements of the spacetime around the black hole, and it will basically measure the shape of the black hole. In the same way, NASA scientists have been measuring the shape of the Earth for the past 40 years by sending off rockets and following their orbits around the Earth and this is how it was first discovered that the Earth is pear-shaped. Knowing the shape of black holes will tell us whether the theory of relativity is right and whether these things that we call black holes in the newspapers really are black holes as described by the theory of relativity. We think they are but we don't actually know it.

The coolest thing LISA will do is to allow us to actually see one black hole spiraling into another black hole. When the horizons zip themselves together and make a new black hole and we are able to measure the ringdown and the shaking of spacetime in that final merger, I think that will be one of the great moments in human history. But it is also fun for me to listen to the engineers and physicists who have been designing LISA and to do little calculations on the back of an envelope and find out how this amazingly precise instrument actually works and all subtle effects you have to worry about to get it to work. It's a great combination of physics and engineering, because it is such a subtle instrument.

LISA is an important mission for some people because it provides a means of directly detecting gravitational waves, which are one of the great predictions of Einstein's theory of relativity. But I'm so convinced that gravitational waves exist, because we have astronomical evidence that they are radiated by two orbiting stars, that the detection of gravitational waves is not quite so interesting as it might have been 30 years ago. For me the interest is in using the gravitational waves to measure all kinds of other things we can't otherwise see or find out about in the Universe.